RELATION BETWEEN UPPER AIR LOWS AND WINTER PRECIPITATION IN THE WESTERN PLATEAU STATES*

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ABSTRACT

A comparison is made of the relative effectiveness of the cyclonic circulation pattern at four different tropospheric levels in specifying winter precipitation over the intermountain area of the western United States. This is accomplished by developing the synoptic climatology of precipitation resulting from Lows at the 850-, 700-, 500-, and 300-mb. levels. Twelve-hr. precipitation amounts (expressed as a percent of the 7-day normal) at 280 stations in the Plateau States for 13 yr. are related to the positions of nearby low centers through a computer system of moving coordinates. For each level, the upper Lows are classified into three intensity categories according to the departure from normal of their central heights. Average precipitation amount, distribution, and frequency of occurrence are then calculated for the area of the grid system. The dependence of these precipitation characteristics upon the level, intensity, and location of the upper Low is described and illustrated. The geographical distribution of Lows at the four upper levels and a schematic model of their associated precipitation are also presented. It is concluded that the effectiveness of upper Lows in producing precipitation generally varies directly with their intensity and inversely with elevation.

1. INTRODUCTION

Previous studies [13] and [6] have shown that storm systems characterized by cyclonic circulation aloft are one of the most important causes of nonsummer precipitation in the western mountain region of the United States. These systems are mainly phenomena of the lower and middle troposphere, but they may frequently extend to higher levels of the atmosphere. Their dynamics can produce upward air motions resulting in precipitation over a wide area, which is then augmented or diminished by orographic factors.

In an earlier paper [4] the authors derived the synoptic climatology of precipitation in the Plateau region as a function of the position and intensity of low centers at the 700-mb. level. In the present paper this investigation will be extended to three additional constant pressure levels, namely, 850, 500, and 300 mb. A comparison will be made of the relative effectiveness of Lows at each of these upper levels in specifying the frequency, amount, and distribution of winter precipitation over the intermountain region. In addition, interesting climatological information will be presented on the geographical distribution of upper Lows at various levels, and a schematic model will be developed for precipitation as a function of the contour pattern.

*Part of this paper was presented at the American Meteorological Society Conference on Physical Processes in the Lower Atmosphere, Ann Arbor, Mich., March 20-22, 1967.

The basic method of data processing was similar to that described in our earlier paper [4] and consisted of applying a computer system of moving coordinates [2] to 13 winters of historical records. This procedure yielded the average frequency and amount of precipitation over a grid network with all low centers placed at the origin and assigned to one of three intensity classes. For the sake of completeness, details of the method used in this study are included in the appendix.

2. DISTRIBUTION OF PRECIPITATION

Charts derived by the procedure described in the appendix bring out three dimensional relationships between characteristics of cyclonic circulation in the lower and middle troposphere and the resulting precipitation. These charts are presented separately for each of the three classes of low intensity, but with the four upper levels side by side. Figures 1–3 give the frequency of measurable amounts (equal to the empirical probability of precipitation), while figures 4–6 give the average 12-hr. amounts of precipitation (expressed as percentages of the 7-day station normals).

Figure 1 shows the analyses of precipitation frequencies for the weakest Lows of Class I. There is little systematic variation of frequency with either position or level. The frequencies range from 0 to 25 percent, but most areas of the grid indicate values not far from 10–15 percent. Climatological probabilities of measurable precipitation

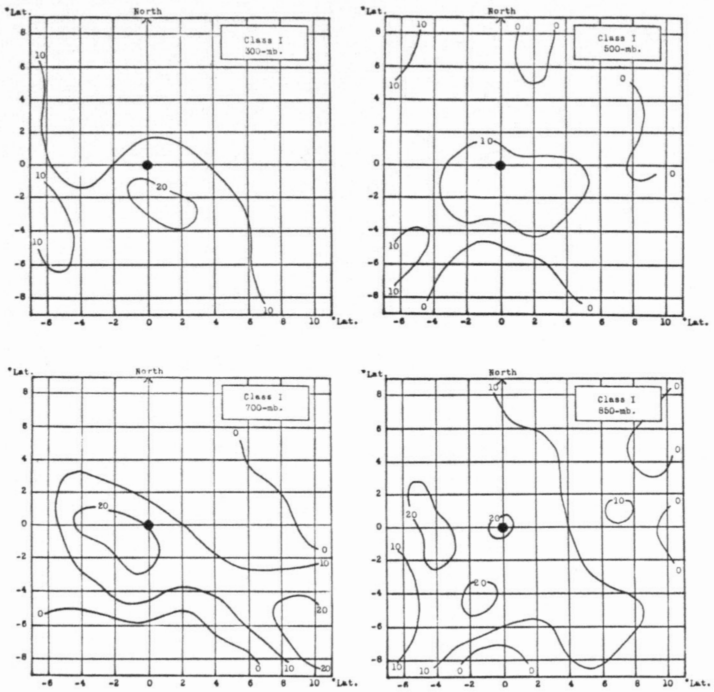

FIGURE 1.—Comparison of frequencies of occurrence of measurable precipitation (in percent) for the four different levels for 12-hr. periods with the weakest Lows (Class I) at the origin. Precipitation amounts are equal to or greater than 1 percent of the 7-day station normal.

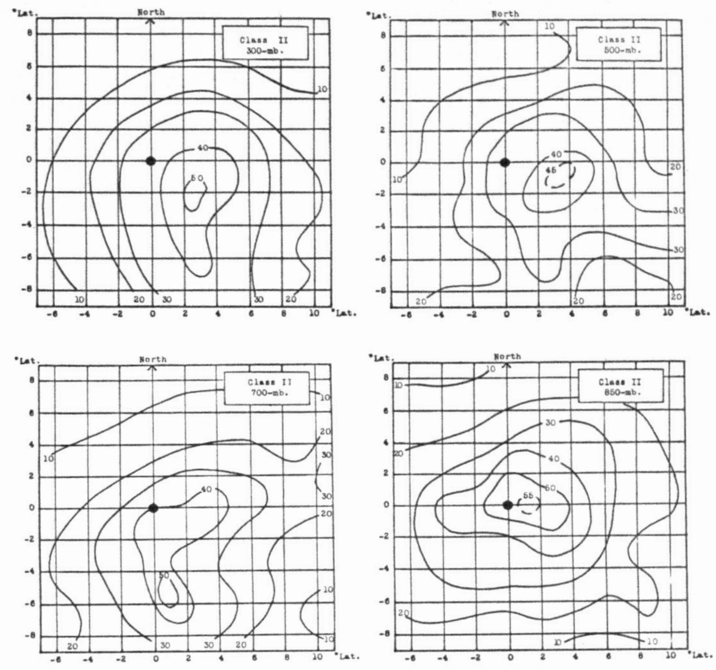

FIGURE 2.—Same as figure 1 except for Lows of intermediate intensity (Class II).

in the Plateau region during 12-hr. periods in winter vary from less than 5 percent in the south to around 30 percent in the extreme north position [3]. Thus it may be concluded that Class I Lows at any level have little effect upon the climatological expectancy of precipitation occurrence.

Figure 2 gives frequencies of occurrence for the intermediate Lows of Class II. At all levels over most of the grid, frequencies are considerably higher than in figure 1. Furthermore, the isopleth patterns are better organized and generally depict an area of maximum frequency east and southeast of the low center (origin). Frequencies in this area of maximum are near 50 percent at all levels.

Frequencies of occurrence for the most intense Lows of Class III are given in figure 3. A further increase in frequency over most of the grid can be noted at all levels, with highest values exceeding 75 percent in an area centered about 2° east-northeast of the low center at 850 mb. Thus we see that, with increasing intensity of the cyclonic system, the frequency of precipitation increases markedly and the area of higher values expands substantially.

Similar characteristics are revealed by the charts for average 12-hr. amounts of precipitation. Figure 4 shows that only light amounts are associated with the weak Lows of Class I, with values ranging from 0 to 20 percent of the weekly normal. The isopleth patterns are not well defined, and there is little difference between the various levels.

Figure 5 shows considerably greater amounts of precipitation for Class II or intermediate Lows. At each level the small area enclosed by the 10-percent line in figure 4 has expanded to include approximately half the grid area. Maximum amounts now range from 35 percent of the weekly normal at 500 and 700 mb. to over 40 percent at the other two levels. The distance of the maximum area from the low center increases steadily with increasing elevation.

The heaviest amounts of precipitation are associated with the deepest Lows of Class III. Figure 6 shows that maximum values east of the origin now exceed 40 percent at all levels, with amounts over 75 percent concentrated in a small area about 2° northeast of the low center at 850 mb. Note the strong gradient north of this maximum, where amounts drop from 75 to 10 percent within about 3° of latitude. Thus, precipitation amounts, like frequencies of occurrence, increase with increasing intensity and lower elevation of the associated low centers.

In order to more readily compare the effectiveness of the four upper levels and three intensity classes in specifying precipitation frequency and amount, the maximum values observed in figures 1–6 were plotted in the form of bar graphs, figure 7. For the Class I Lows, no single level stands out as giving the best results for both frequency and amount. The Class II situations show a slightly decreasing trend with height for the centers of maximum frequency, but no overall tendency for maximum amounts. The maximum values for both frequency and amount for

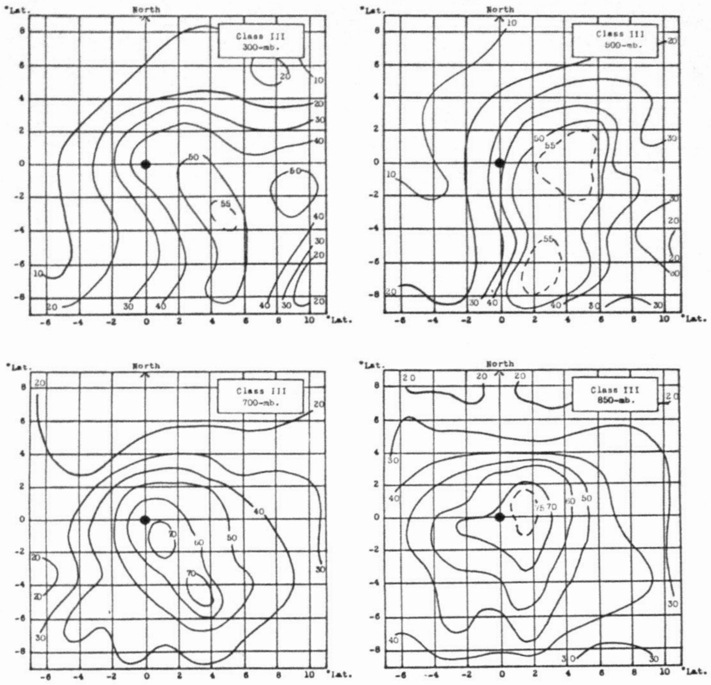

FIGURE 3.—Same as figure 1 except for the most intense Lows (Class III).

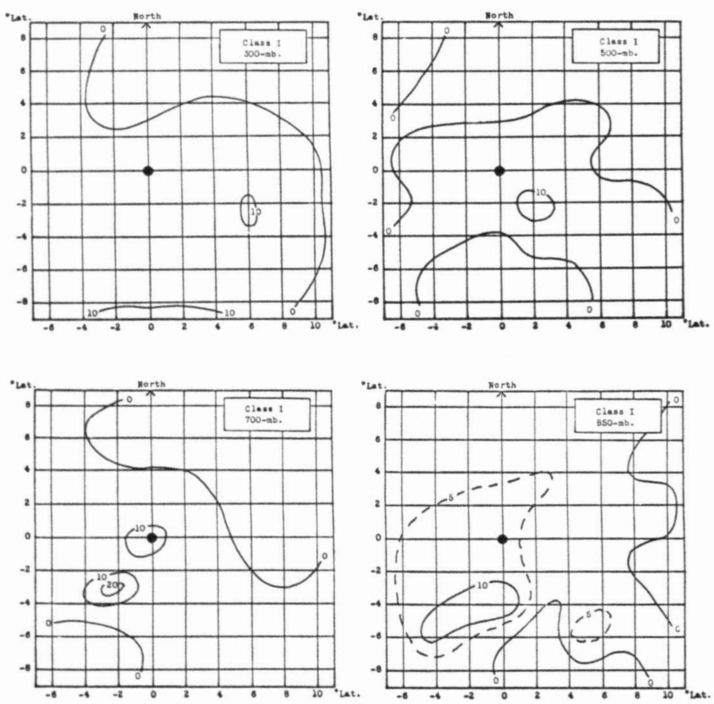

FIGURE 4.—Comparison of precipitation amounts for the four different levels with the weakest Lows (Class I) at the origin. Amounts during the 12-hr. period centered at times of upper air observations are expressed as percentages of 7-day station normals.

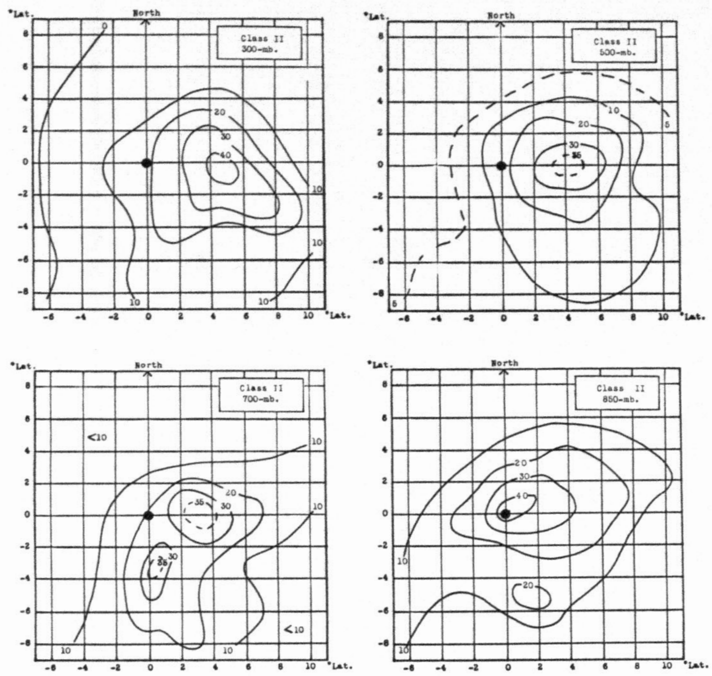

FIGURE 5.—Same as figure 4 except for Lows of intermediate intensity (Class II).

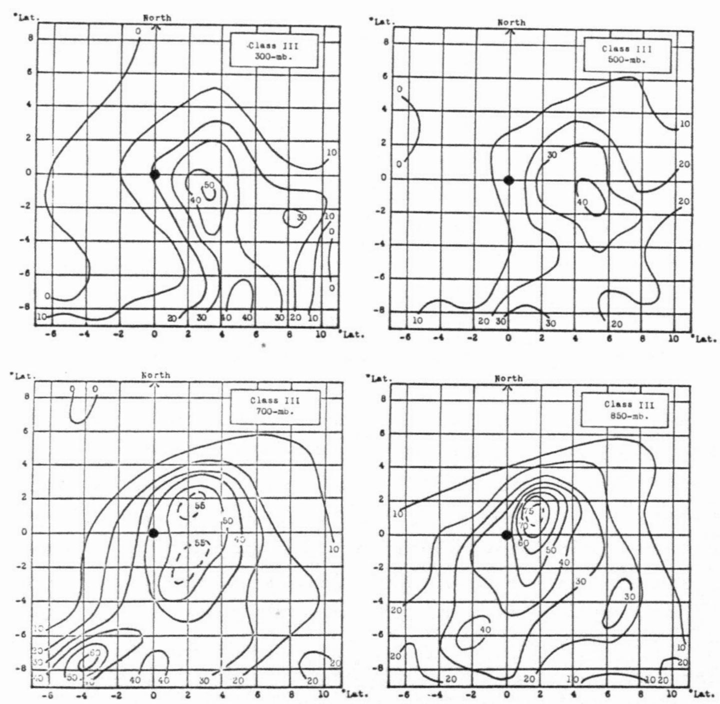

FIGURE 6.—Same as figure 4 except for the most intense Lows (Class III).

this Class fall between the corresponding values for Classes I and III at all four levels.

For the most intense Lows of Class III, figure 7 shows a clear and definite decrease in the specification of precipitation in going from lower to higher levels. This is especially marked for the maximum frequency of occurrence, where each succeeding level indicates a lower value in making the comparison upwards from 850 to 300 mb. The same trend is shown for the maximum amounts, except that here the 500-mb. level has the lowest value.

The location of the centroids of maximum precipitation in figures 1–6 in relation to the position of the Lows at

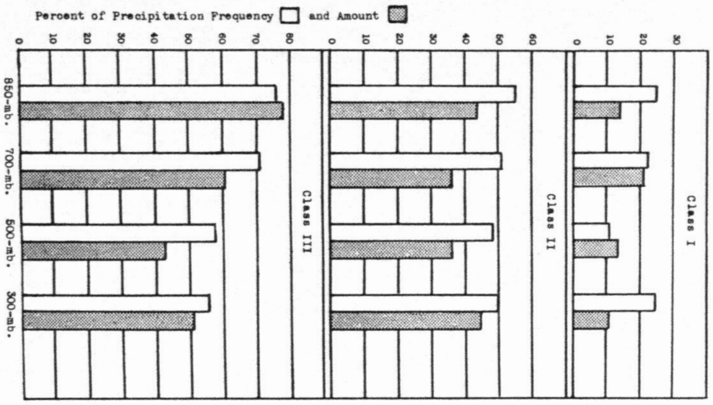

FIGURE 7.—Bar graphs showing the relative effectiveness of the four levels in specifying maximum values of precipitation frequency (from figs. 1–3) and amount (from figs. 4–6) for Lows of each intensity class.

the various levels sheds additional light on the structure of the cyclonic systems. An illustrative chart is given in figure 8 for the relative position of the centers of maximum frequency for the Class III situations. In interpreting this figure, the assumption can be made that the frequency centers at the four levels represent the same general area relative to the cyclonic systems, since the majority of storms studied were common to all levels. It can then be seen that the centers of the most intense Lows are closest to the centers of maximum precipitation frequency at the lowest level (850 mb.) and then become displaced progressively farther to the northwest at higher levels. This results from the slope of the axis of the closed circulation towards the cold air, which is generally located north and west of the surface center. Thus the "average" storm in Class III at 850 mb. is about 2° latitude west of the centroid of maximum frequency and has an axis sloping about 2° northward from 850 to 700 mb., about 2° northwestward from 700 to 500 mb., and about 1° westward from 500 to 300 mb.

Schematic contours have been drawn around the position of the low center in figure 8 in order to produce a synoptic model of precipitation occurrence. It can then be seen that the optimum area for precipitation in the Plateau region during winter is located about 2° east of a deep low center at the 850-mb. level, in a region of southerly geostrophic flow. Precipitation is most likely to occur about 3° southeast of the low center at 700 mb., in a region of southwesterly geostrophic flow. Precipitation is also most frequent under southwesterly flow in the southeast quadrant of deep Lows at 500 and 300 mb., but at increased distances from the low center, about 5 and 6° of latitude, respectively. Similar models can be derived for the other intensity classes and for precipitation amounts, but they will not be reproduced here.

3. DISTRIBUTION OF LOWS

Table 1 gives the frequency of Lows considered in this study by level and by class. The last column shows that

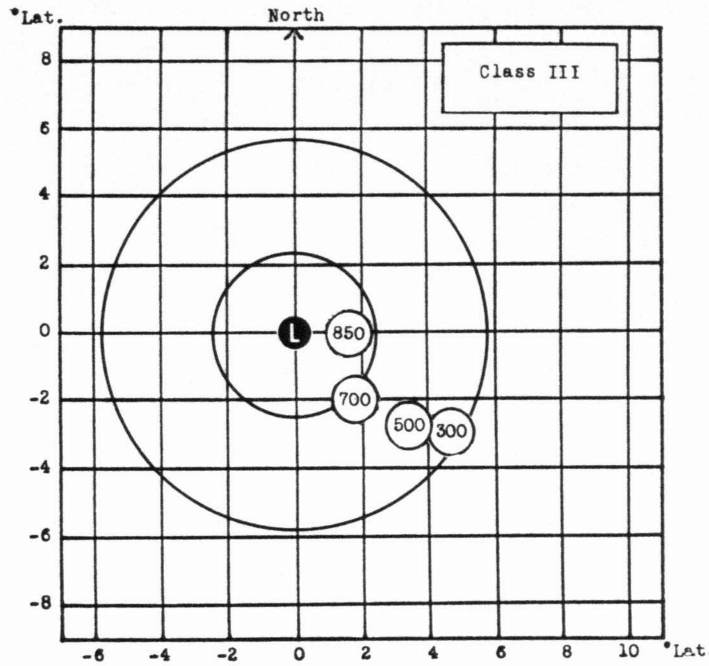

FIGURE 8.—Areas of maximum frequency of occurrence of measurable precipitation with the most intense Lows (Class III) centered at the origin for 850-, 700-, 500-, and 300-mb. levels. The symmetrical circles represent idealized contours about the low center at any level.

TABLE 1—*The number of major Lows studied at each level and in each intensity category*

Level in millibars	Class I	Class II	Class III	All classes
850	316	509	285	1110
700	216	423	233	872
500	220	483	172	875
300	175	348	139	662

the total number of Lows was about 60 percent greater at 850 than at 300 mb., with intermediate values at 700 and 500 mb. This reflects the well-known tendency for surface Lows at middle latitudes to be surmounted aloft by open wave troughs. It also means that the precipitation distributions of figures 1–6 are more reliable and can be applied more frequently at the lower levels.

The geographical distribution of the low centers is given in figure 9, separately for each of the four upper levels but for all intensity classes combined. This procedure was followed in order to increase the reliability of the results because separate diagrams for each class (not reproduced) did not reveal any significant dependence of distribution upon intensity. The Lows were counted within 2° latitude squares, and the resultant frequencies of occurrence are depicted by the isopleths in this figure.

Figure 9 is of general climatological interest, although its main features are similar to those of previous studies on cyclone frequency at sea level [5], 700 mb. [10], and 500 mb. [1]. Lows at all levels occur least frequently over

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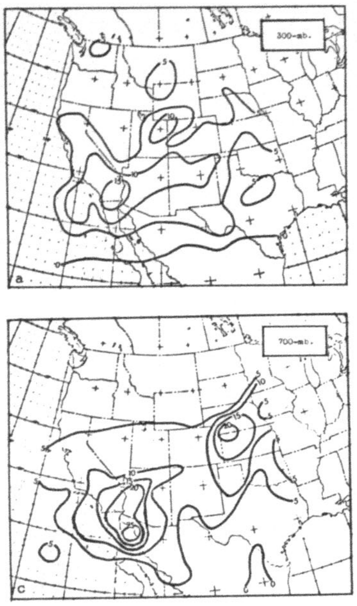

FIGURE 9.—Distribution of major Lows of all intensities at four upper levels over the area of figure 10 during the winter months, December 1951–February 1964. Frequencies are analyzed as the total number of occurrences during the period per 2° latitude square.

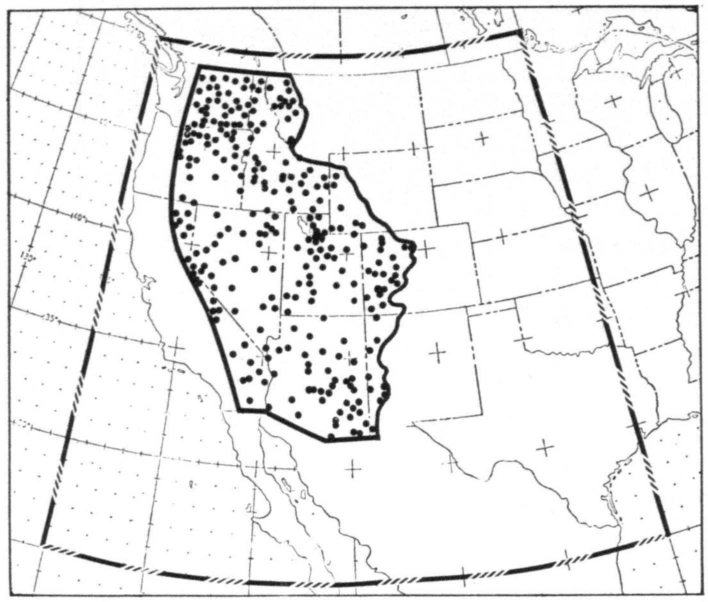

FIGURE 10.—Observational area (enclosed by heavy dashed lines) within which upper Lows were considered and precipitation station network (black dots).

the northern portion of the area and along the southern boundary. Maximum frequencies are found east of the Continental Divide at the lower levels and west of the Divide at the higher levels. Note how cyclone frequency decreases with increasing elevation in the Great Plains, where Lows are frequently shallow and warm, and increases with increasing elevation (up to 500 mb.) near the southern edge of California, where deep cold Lows are common.

4. CONCLUSION

This investigation has revealed a surprisingly close relation between precipitation and circulation, particularly in the case of intense Lows at lower levels. These relations should prove useful in a diagnostic sense in planning, interpreting, and evaluating activities in the field of weather modification. With continued improvement in the accuracy of operational numerical prediction [12], figures 1–6 can be applied routinely to prognostic charts and used as forecast nomograms to give a first estimate of the probability, distribution, and amount of precipitation to be expected in the Plateau region for any situation involving a low center at upper levels over the Western States.

The results of this paper show that there are significant variations between the different tropospheric levels in ability to specify precipitation frequency and amount from upper Lows. In general, the lower the level, the better appears to be the relationship to precipitation. Similar results were recently obtained in specifying the probability of winter precipitation over the eastern half of the United States from numerous circulation characteristics at the 1000-, 700-, and 500-mb. levels [11], and in relating winter precipitation categories over the Tennessee Valley to height fields at 1000- and 700-mb. levels [7].

Since the 850-mb. level is close to the surface in the Plateau region, the findings of this study and those cited above may be generalized by concluding that precipitation, at least in winter, appears to be more closely related to the circulation at the surface than at any upper level.

APPENDIX—DATA PROCESSING

The period investigated comprised the winter months from December 1951 through February 1964. For each of these 39 months and each of the four upper levels (850, 700, 500, and 300 mb.), twice-daily maps (0300 and 1500 GMT, except 3 hr. earlier after June 1, 1957) analyzed in the National Meteorological Center (NMC), Suitland, Md., were carefully examined to see whether any low center was located within the region bounded by the heavy dashed lines of figure 10. If so, the central intensity and location of the Low were estimated from the contour field and plotted station reports. All centers of cyclonic circulation were included in this tabulation, whether or not a closed contour was present on the analyzed map, except that only the major Low was used in cases with more than one center over the area of interest.

In order to minimize the effects of spatial and temporal variations in normal height patterns, and thus make Lows in different areas and months more nearly comparable, the intensity of each low center was expressed in terms of its departure from normal. This was done by subtracting from its central height the normal height appropriate to its location and month of occurrence. Normal heights were obtained from harmonically smoothed monthly mean maps developed for this investigation at 850 and 500 mb., and from other sources at 700 mb. [9] and 300 mb. [8]. Although an attempt

TABLE 2.—*Characteristics of normal maps used to obtain departures from normal of heights at various levels*

Level	Period of record	Map interval	Source	Grid used	Map time (GMT)
850 mb	Nov. 1, 1958–Oct. 31, 1965	Bimonthly	NMC	Square	00
700 mb	Jan. 1, 1946–Dec. 31, 1963	Bimonthly	[9]	Diamond	00, 03, 12, & 15
500 mb	Nov. 1, 1958–Oct. 31, 1965	Bimonthly	NMC	Square	00
300 mb	Jan. 1, 1950–Dec. 31, 1957	Monthly	[8]	Diamond	15

TABLE 3.—*Class limits (in meters) of departures from normal of central heights for Lows at foxr levels*

Millibar level	Class I	Class II	Class III
850	>−45	−45 to −120	<−120
700	>−31	−31 to −124	<−124
500	>−60	−60 to −242	<−242
300	>−122	−122 to −332	<−332

was made to utilize the most reliable normal maps available, they had different properties at each level, as summarized in table 2. This lack of homogeneity was assumed negligible for the purpose of this study, as also were all diurnal effects and spatial variation of the standard deviation of height.

To further simplify the data processing, the low centers at each level were classified into three intensity categories of nearly equal range. This was done by ranking the Lows in order of their central height departures from normal and then establishing convenient cutoff points for classes within the frequency distribution. The exact class limits used for each level are listed in table 3. Note that Class I represents the least intense or weakest Lows, while Class III includes only the most intense or deepest systems. The Class II Lows of intermediate or average intensity are the most numerous of any class (table 1).

Hourly precipitation data were obtained from the National Weather Records Center (NWRC), Asheville, N.C., and accumulated to give 12-hr. amounts centered at times of the upper air maps (0000 or 0300 GMT and 1200 or 1500 GMT). A dense network of 280 stations was used, shown by black dots in figure 10. These stations are located in the Plateau region of the United States, between the Continental Divide on the east and the Cascade-Sierra Nevada chain of mountains on the west.

All precipitation amounts were expressed as percentages of the 7-day station normals to eliminate as much as possible the variability of precipitation due to differing station elevation and local orographic effects, thus making observations at individual stations more directly comparable. Generally the normals were based on a 10-yr. precipitation record furnished by NWRC. Seven days were used as the normal period because normal values were desired for which 1 percent to 5 percent would represent the smallest measurable amount, i.e., 0.01 in. This requirement was closely approximated when the 7-day normal precipitation amount was used in the Plateau region during winter.

The 12-hr. precipitation percentages at each station were related to the positions of the nearby low centers through a computer system of moving coordinates [2]. This was done separately for each of the four upper levels and three intensity classes by use of the grid shown in figure 11. In each case the grid was considered to be moving with the low center, which was placed at the origin (heavy black dot) of the coordinate system. The grid network was made up of 324 cells, approximately 1° of latitude square, formed by the intersections of great circles (assumed to be straight lines on a Lambert Conformal projection) over an area 18° of latitude on a side. Note that the origin in figure 11 is displaced 2° westward because more precipitation was expected east of the low center.

A computer program at NWRC scanned the precipitation percentages reported by each observing station of figure 10 and allocated them to the correct cell. By combining all Lows for a given level and intensity class, the computer then obtained the average percentage within each cell for Lows of that category. These data were

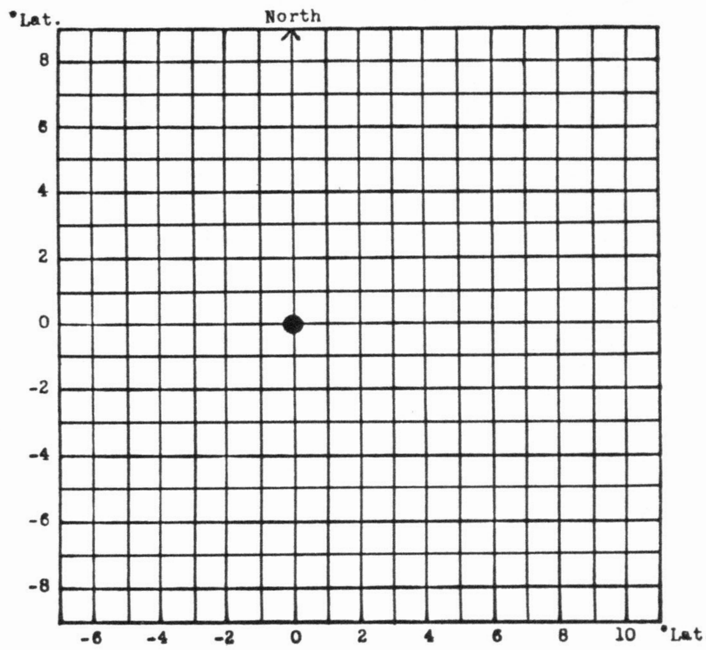

FIGURE 11.—Grid representation on plane surface. Grid system consists of great circles on the spherical earth with dimensional units equivalent to latitude degrees along the two axes.

plotted and analyzed to give charts showing the average distribution of precipitation about low centers of various types. Note that this procedure treats the Plateau region as a relatively homogeneous area for the purposes of this study. This assumption is tenable because all heights have been expressed as departures from normal and all precipitation amounts as percentages of normal.

ACKNOWLEDGMENT

This investigation was accomplished through the financial support of the Bureau of Reclamation, Department of the Interior. Data accumulation and computer processing were carried out by the National Weather Records Center, Asheville, N.C. Normal maps at the 700-mb. level were supplied by the Extended Forecast Division of the National Meteorological Center. Normal maps at 850 and 500 mb. were calculated from NMC grid point data by means of a computer program of harmonic analysis written by Mr. Frank Lewis and Mr. Clifton K. S. Chun of the Techniques Development Laboratory. Assistance in manually processing data for this paper was provided by Mrs. Mary M. Abernathy, Mr. James A. Bunce, Jr., Mrs. Normalee S. Foat, and Mr. Richard J. Naistat of the Techniques Development Laboratory.

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[*Received August 1, 1967; revised December 13, 1967*]